The Effect of Magnetization on the Thermoelectrical and other Physical Properties of Bismuth

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XX. *The Effect of Magnetization on the Thermoelectrical and other Physical Properties of Bismuth.* By HERBERT TOMLINSON, *B.A.**

IN a paper read before the Royal Society on January 26, 1882†, the author has given an account of an experiment relating to the effect of longitudinal magnetization on the electrical resistance of bismuth. The subject has since been taken up much more fully by Righi ‡, Leduc §, Hurion ‖, and Albert v. Ettingshausen and Walther Nernst¶. In the author's paper quoted above are also described experiments on the effects of magnetization on the electrical resistance of iron, steel, nickel, and cobalt, the results of which are summarized in the following table:—

TABLE I.

Metal.	Condition.	Increase of resistance per unit produced by a C.G.S. unit of magnetizing force, $\frac{\Delta r}{rM_f}$.	Magnetic susceptibility. κ**.	$\frac{\Delta r}{rM_f}/\kappa$**.
Iron	Annealed.	2335×10^{-8}.	30	0.8×10^{-6}
Steel	Annealed.	1500 „		
Steel	Unannealed.	1137 „		
Steel	Very hard.	70 „		
Nickel	Annealed.	8070 „	8·8	9·2 „
Nickel	Unannealed.	4343 „		
Cobalt. ...	Unannealed.	638 „	4·4	1·4 „
Bismuth ...	Unannealed.	21 „	—·000014††	1500 „
Copper ...	Annealed.	0‡‡ „		

* Read January 28, 1888.

† "The Influence of Stress and Strain on the Physical Properties of Matter," Phil. Trans. vol. clxxiv. (1883, part 1). Abstract, Proc. Roy. Soc. No. 218 (1882).

‡ *Acc. R. dei Lincei*, 1883, 1884.

§ *Bull. de la Soc. française de Phys.* 1884.

‖ *Comptes Rendus*, 1884, 1885.

¶ *Sitzb. der kais. Akad. der Wissensch.* 1887.

** The values of κ were determined for the same magnetizing forces as those used for producing alteration of resistance.

†† Taken from Von Ettingshausen's determinations (*Wien. Ber.* 1882).

‡‡ No change amounting to $\frac{1}{4000000}$ could be detected with a magnetizing force of 90 C.G.S. units.

The data in this table refer to the effects of *temporary* magnetization; and in the case of iron, steel, and nickel, represent only verifications and extensions of the labours of previous observers. Abraham, Edlund, Mousson, and Wartmann all made search for magnetic alteration of the resistance of iron. W. Thomson * seems, however, to have been the first to arrive at any definite result. He found the resistance to be increased along the lines of magnetization and decreased across them. W. Thomson has been followed by Beetz †, Tomlinson ‡, Chwolson §, Auerbach ‖, and De Lucchi ¶. These have all confirmed the results of Thomson so far as longitudinal magnetization is concerned; but Beetz failed to obtain anything but negative results with transverse magnetization, and attributed the decrease of resistance observed by Thomson to mere mechanical pull. The author has, however, pointed out** the improbability of this last supposition. W. Thomson had also previously proved †† that the electrical resistance of nickel is increased to a greater extent than that of iron by longidinal magnetization; whilst Faé ‡‡ has recently verified the author's result concerning cobalt. Lastly, Goldhammer §§ has published a comparative study of the three paramagnetic metals—iron, cobalt, and nickel, and of the three diamagnetic metals—bismuth, antimony, and tellurium ‖‖.

There are several points in the table given above to which it is desirable to direct attention. In the first place the resistance of all the metals is *increased* by longitudinal magnetization. In the second it by no means always follows that the metals which possess the greatest magnetic susceptibility are those which are most affected in their conductivity by a given amount of magnetizing-stress. We see, for instance, from the third and fourth columns, that whilst the value of $\frac{\Delta r}{r\mathrm{M}_f}$ for

* "Electrodynamic Qualities of Metals," Phil. Trans. 1856, Part iv.

† Pogg. *Ann.* vol. cxxviii. (1886).

‡ Proc. Roy. Soc. vol. xxiii. (1875). Also *loc. cit.*

§ Carl's *Rep.* vol. xiii. (1877).

‖ Phil. Mag. vol. viii. (1879).

¶ *Atti del R. Ist. Veneto*, viii. (1882).

** *Loc. cit.* pp. 165, 166.

†† Proc. Roy. Soc. vol. viii. (1857).

‡‡ *Atti del R. Ist. Veneto*, 1887.

§§ Wied. *Ann.* xxxi. (1887).

‖‖ See also a memoir, entitled "An Experimental Study of the Influence of Magnetism and Temperature on the Electrical Resistance of Bismuth and its Alloys with Lead and Tin," by Edmond van Aubel. *Ante*, p. 124.

nickel is twice that for iron, the magnetic susceptibility of iron is between three and four times as great as that of nickel. It is, however, when we come to consider the fifth column that we meet with the most remarkable differences in the effects of magnetization. The numbers in this column represent the increase of resistance per unit which would be produced in each of the metals by magnetizing them to such an extent that each cubic centimetre would possess unit magnetic moment. The effect of the magnetization in this case would be nearly twice as great for cobalt as for iron, twelve times as great for nickel as for iron, and, speaking very roughly, *two thousand* times as great for bismuth as for iron. Startling as this last result is, it sinks into insignificance when contrasted with the results obtained by other observers. The effect of magnetization on the electrical resistance of bismuth is largely influenced, amongst other things, by the amount of impurity in the metal and the magnitude of the magnetizing force. Thus, from Ettingshausen's researches, from which Table II. has been compiled, we learn that the value of $\frac{\Delta r}{r\mathrm{M}_f}$ for pure bismuth and for very large magnetizing forces* may become nearly 200 times as great as

TABLE II.

Transverse Magnetization.

Magnetizing force, in C.G.S. units.	Increase of resistance per unit produced in pure bismuth by a C.G.S. unit of magnetizing force, $\frac{\Delta r}{r\mathrm{M}_f}$.	Ditto in bismuth alloyed with one per cent. of tin.
1600	1610×10^{-8}	
3160	2490 „	
5880	3350 „	
8410	3660 „	660×10^{-8}
10470	3840 „	
11200	3890 „	

* The bismuth was acted upon by a transverse magnetizing force, which, however, has been proved to *increase* the resistance, though to a greater extent than a longitudinally magnetizing force.

that observed by the author*, with the comparatively low magnetizing force of 130 C.G.S. units ; whilst the introduction of one per cent. of tin diminishes the value to *one sixth.* Provided that the susceptibility of bismuth be the same for very high magnetizing forces as for low ones, it would follow that if a bar of pure bismuth could be magnetized to unit intensity† its resistance would be nearly trebled, whilst the increase of resistance per unit would be at least 300,000 times as great as the corresponding change of resistance in iron. Considerations such as the above render it difficult to believe that what is observed in bismuth in such experiments as these is a real change in the specific resistance of the metal ; and even with iron, nickel, and cobalt there seems to be evidence that the *whole* of the observed change produced by magnetization is not produced by mere rotation of the molecules. In the author's experiments on iron and nickel he found that the increase of resistance could be very closely represented by the formula

$$\frac{\Delta r}{r} = a\mathrm{M}_f + b\mathrm{M} \;;$$

where $\frac{\Delta r}{r}$ denotes the increase of resistance per unit, and M_f and M_i are the magnetizing force and the magnetic intensity respectively. From this formula it follows that, even if the magnetizing force were so high that the ratio of increase of intensity to increase of force was extremely small, the resistance would nevertheless go on increasing very perceptibly indeed with the force. The values of the coefficient b were not very different in the two metals nickel and iron ; but the coefficient a in nickel was about five times as great as in iron, and was nearly double the coefficient b. It would be a matter of considerable interest to ascertain whether it would really happen that, when very great magnetizing forces were employed, the resistance of nickel would go on increasing very perceptibly with the force‡.

* The specimen of bismuth used by the author has been, through the kindness of Professor J. M. Thomson, analyzed at the chemical laboratory at King's College, London ; it contains 98·48 per cent. of bismuth.

† This would require a magnetizing force of 71,000 C.G.S. units.

‡ The magnitudes of the forces used by the author never exceeded 200 C.G.S. units.

If, however, on the one hand there is a difficulty in conceiving how magnetization can so largely affect the true specific resistance of bismuth, there is also an equal difficulty in accounting otherwise for what is observed. Hall's phenomenon cannot certainly be credited in any of the experiments which have yet been made with anything but a small fraction of the whole observed effect. It is true that bismuth has been found by Righi and others to have a very large rotational coefficient as compared with iron, nickel, or cobalt; but Ettingshausen and Nernst have shown* that whilst, with bismuth, antimony, and tellurium, the increase per unit of resistance produced by a magnetizing force of 7660 C.G.S. units is 0·20, 0·006, and 0·0014 respectively, the corresponding values of the rotatory power are −4·7, +0·18, and +790.

Neither, again, can the change of dimensions produced by magnetization in any of the metals be accountable for the increase of resistance. For though, curiously enough, loading an iron wire increases the resistance, and magnetizing it longitudinally increases the length, whilst loading a nickel wire† *decreases* the resistance and magnetization *decreases* the length, yet, according to Joule and others, when an iron wire is loaded to a certain extent longitudinal magnetization begins to decrease the length; whereas the author has shown that, even when iron is loaded nearly to breaking, longitudinal magnetization always produces increase of resistance. Besides, the changes of dimensions in nickel, iron, and bismuth produced by magnetization are far too small‡. Here again, however, it should be noticed that both the decrease of length produced by magnetization and the decrease of resistance produced by loading a nickel wire are considerably greater than the corresponding increase in the case of iron.

Whatever it is that causes magnetization to produce so large an effect on the electrical conductivity of bismuth, causes it to produce also a large effect on some of the other physical properties. The thermal conductivity of bismuth is, according to Leduc§ and Righi ||, decreased both by longitudinal and

* *Loc. cit.* † See Phil. Trans. 1883.

‡ Prof. Barrett failed to detect any change produced in the dimensions of bismuth by magnetization.

§ *Comptes Rendus*, 1887. || *Ibid.*

transverse magnetization by an amount which is about equal to the amount of decrease produced in the electrical conductivity; and though it would appear, from Ettingshausen's observations*, that the decrease of thermal conductivity is decidedly less than the decrease of electrical conductivity, yet even this observer makes the former comparable with the latter; and we shall now see that the thermoelectrical properties of bismuth are quite as largely affected by magnetization as either the thermal or the electrical conductivity.

The Thermoelectrical Properties of Bismuth.

Sir W. Thomson has shown † that iron longitudinally magnetized is negative, and transversely magnetized positive, to iron unmagnetized. Barus and Strouhal ‡ have also investigated with great completeness the influence of magnetization on the thermoelectrical properties of steel of different tempers. Finally, Ewing has entered very fully § into the changes effected by longitudinal magnetization in iron when under different amounts of longitudinal stress. Thomson has also shown ‖ that nickel is rendered by longitudinal magnetization thermoelectrically positive to unmagnetized nickel; whilst the author has found ¶ cobalt when under longitudinal magnetization to be negative to the unmagnetized metal.

The experiment now about to be described was made nearly at the same period as the experiment on the effect of magnetization on the electrical resistance of bismuth and with the same bar. This bar was 25 centim. long and 0·33 centim. in diameter; it was placed in the axis of a magnetizing solenoid, S, specially constructed to avoid imparting heat to the magnetized core**; a preliminary examination proved that there was certainly no error arising from this cause. The arrangements are sufficiently shown in fig. 1, where S is the solenoid and A B the bar. The bar was encircled by two little air-chambers, C and D, through one of which steam was

* *Annalen der Physik und Chemie*, Band xxxiii. (1888).

† "Electrodynamic Qualities of Metals," Phil. Trans. Part iv. 1856.

‡ Bulletin of the U. S. Geological Survey, No. 14 (1885).

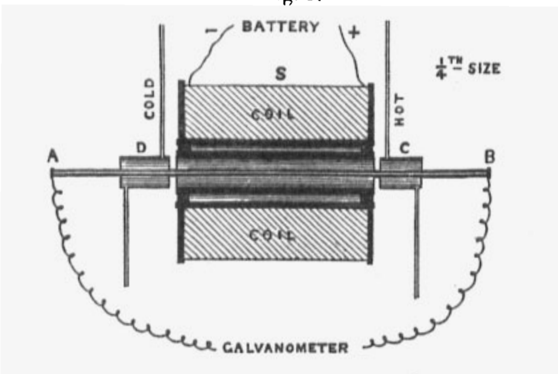
§ Phil. Trans. Part ii. 1886. ‖ *Loc. cit.*

¶ Proc. Roy. Soc. No. 241 (1885).

** For a description of this solenoid see Phil. Trans. 1883, *loc. cit.*

passed, and through the other water at a temperature of about 16° C. The ends A and B were connected by copper wires

Fig. 1.



with a very sensitive Thomson's reflecting-galvanometer, and were well buried in sawdust.

Since a bar of bismuth can never be obtained in a perfectly homogeneous condition throughout its whole length, there was a considerable thermoelectrical current already in existence before magnetization and the spot of light was driven off the scale. The light could be again brought on the scale by putting the adjusting-magnet low down; but this of course materially diminished the sensibility of the galvanometer, and as the effect to be looked for was likely to be very small this was not desirable. Accordingly the following plan was adopted:—There were two sets of needles in the galvanometer, connected with each other and the mirror; round one set was wound a coil of about 6000 ohms resistance, and round the other a coil of between 7 and 8 ohms resistance; the extremities of these coils were attached to separate terminals, and the latter coil was employed to measure the thermoelectrical effect of magnetization. The thermoelectrical current due to want of homogeneousness in the bismuth was balanced by the current from a Daniell cell sent through the other coil, which was shunted, and through a very large resistance: by altering this resistance the spot of light could easily be brought again to the middle of the scale. Some two hours were allowed to elapse, the steam during the whole of this time passing through the air-chamber, C, and the cold water through the air-chamber, D, after which the spot of light remained steady. The solenoid, S, was now actuated by a current from six Grove cells, and a deflection ensued indicating a current *from unmagnetized to magnetized bismuth through the hot junction.* The current through the solenoid was then stopped, and the spot of light returned sensibly to its old position. The observation was repeated ten times, and then the current through the solenoid being reversed, ten other observations were made, after which the current was again reversed. The readings had to be corrected for a slight direct action of the magnetizing solenoid on the needles of the galvanometer.

The deflection due to the thermoelectrical current between magnetized and unmagnetized bismuth was very small; but, so far as could be made out, it was the same for both directions of the magnetizing current. The mean of the readings gave a deflection of 3·5 divisions of the scale; and, by independent observation with a Daniell cell, it had been ascertained that a deflection of 1 division of the scale would, under the conditions of the experiment, indicate an E.M.F. of 0·143 microvolt. Consequently the E.M.F. produced by temperatures of 100° C. and 16° C. at the two junctions of magnetized and unmagnetized bismuth would be $0{\cdot}143 \times 3{\cdot}5$ microvolts $= \frac{1}{2}$ microvolt. The magnetizing force was 226 C.G.S. units; so that the E.M.F. for unit magnetizing force would be ·0022 microvolt, or ·22 C.G.S. unit of E.M.F. If we divide the last number by 14×10^{-6}, the magnetic susceptibility, we shall obtain the E.M.F. which would be produced by magnetizing the bismuth to unit intensity; this is 15714 C.G.S. units. Now, according to Ewing, the E.M.F. produced in a certain specimen of soft iron wire by a magnetic intensity of 160 C.G.S. units was 6 microvolts, when the junctions of the magnetized and unmagnetized wires were at 100° C. and 16° C. respectively. Accordingly the E.M.F. produced by unit magnetic intensity would be 3·75 C.G.S. From this it is evident that, for a given intensity of magnetization, bismuth has its thermoelectrical properties altered by longitudinal magnetization 4000 times as much as iron. We see, then, that the relative changes produced by magnetization in the thermoelectrical properties of bismuth and iron are comparable with the changes wrought in the electrical and thermal conductivities of these metals.

Grimaldi has already published researches* on the effect of both transverse and longitudinal magnetization on the thermoelectrical properties of bismuth, and finds that magnetization in either of these two directions makes the bismuth of commerce thermoelectrically negative to unmagnetized bismuth. He also finds that the thermoelectrical E.M.F. of a *pure* bismuth and copper couple is increased by both longitudinal and transverse magnetization. Now according to Ettingshausen†, who also quotes Rollmann‡, *pure* bismuth is thermoelectrically *negative* to copper, whilst commercial bismuth is positive to copper. The following table is taken from Ettingshausen's memoir:—

TABLE III.—Bismuth alloyed with different amounts of Tin.

Potential difference, in C.G.S. units, for 1° C. between a bismuth and copper couple with one junction at 20° C. and the other at 0° C.	Number of parts, by weight, of pure bismuth in 100.
−6500	100·00
+ 280	99·05
+1950	98·54
+3910	93·86
+3390	86·90

Consequently it would seem to follow, from Grimaldi's experiments, that *both pure and commercial bismuth* are rendered by magnetization negative to the unmagnetized metal, *i. e.* the thermoelectrical current would flow from unmagnetized bismuth to magnetized bismuth through the hot junction.

Grimaldi shows that, in the following respects, the effect of magnetization on the thermoelectrical properties of bismuth

* *R. Acc. dei Lincei*, vol. iii. Also memoir, entitled *Influenza del Magnetismo sulle Proprietà Termoelettriche del Bismuto* (Palermo, 1887); *Journal de Physique*, Dec. 1887, p. 569.

† *Sitzb. der kais. Akad. der Wissensch.* 1887.

‡ Pogg. *Ann.* lxxxiii., lxxxiv., lxxxix.

resembles the effect of magnetization on the electrical conductivity:—

(1) The amounts of the two effects are comparable with each other.

(2) Transverse magnetization produces a greater effect than longitudinal magnetization.

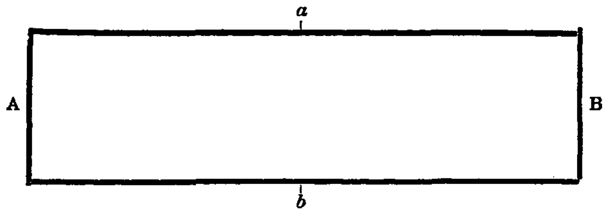
(3) Rise of temperature* diminishes the effect.

(4) The effect increases in greater proportion than the magnetizing force.

It is impossible for the author to compare his own results with those of Grimaldi ; but it would seem from the above that, by using high magnetizing forces and lower temperatures at the junctions, the effect of magnetization on the thermo-electrical properties of bismuth might well be found to be some three or four hundred thousand times the effect in iron, upposing both metals to be magnetized to unit intensity.

This being the case, it is difficult to believe that the alteration due to magnetization is a real alteration of the thermo-electrical power of the metal. But, again, how are we to account for it. According to Ettingshausen†, when a plate of bismuth, A B (fig. 2), is arranged, as for experiments on

Fig. 2.



Hall's phenomenon, with its plane parallel to the flat faces of the pole-pieces of an electromagnet and perpendicular to the lines of force, whilst a current of electricity is conducted longitudinally through the plate, the excitation of the electromagnet produces a difference of temperature at the two points *a* and *b*; whilst, on the contrary, if a current of heat be conducted through the plate instead of the electrical current, there will be produced by the action of the electromagnet a difference

* At least as far as 100° C.

† *Annalen der Physik und Chemie* Band xxxi. (1887).

of potential at the two points* a and b. Further, besides the difference of potential at a and b, which is designated the transverse "thermomagnetic effect," there will be a difference of potential at A and B called the longitudinal thermomagnetic effect; and this last, says Ettingshausen, will account for the apparent effect of magnetization on the thermoelectrical properties of bismuth. Both Grimaldi† and Leduc‡, however, are of opinion that the apparent longitudinal thermomagnetic effect is produced by decrease of thermal conductivity and thermoelectrical power.

The alteration of dimensions produced by magnetization can as little account for the change in the thermoelectrical properties of metals as for the increase of resistance; for, besides the minuteness of the alteration of dimensions, in some cases the effect of loading on the thermoelectrical power is in the same direction, and in others in the opposite direction, to the effect of longitudinal magnetization, as will be seen from Table IV.

TABLE IV.

Metal.	Under longitudinal traction§.	Under longitudinal magnetization ‖.
Iron	−	−
Nickel	+	+
Cobalt	+	−
Bismuth	+¶	−

There is, however, this resemblance between the effects of magnetization on the thermoelectrical properties of iron and on its dimensions. When an iron wire is loaded beyond a certain limit, magnetization begins to produce decrease of length and increase of thermoelectrical power**.

In conclusion, when we contrast the small magnetic sus-

* Ettingshausen and Nernst, Wied. *Ann.* xxix. (1886).

† *Nuovo Cimento*, ser. 3, vol. xxii. (1887).

‡ *Comptes Rendus*, 1887.

§ A plus sign shows that the stretched metal is positive to unstretched.

‖ A plus sign shows that the magnetized metal is positive to unmagnetized.

¶ Righi, *R. Acc. dei Lincei, Transunti* (1884).

** *Cf.* Ewing, *loc. cit.*

ceptibility of bismuth with the large value of its rotational coefficient, and with the large decrease which can be produced both by transverse and longitudinal magnetization in the thermal conductivity, the electrical conductivity, and the thermoelectrical power of the metal, we must be driven to the conclusion that magnetism in all metals exerts two distinct influences ; one by rotation of the molecules about their axes, the other in some way which is not yet understood. In such metals as iron, and to a less extent in cobalt and nickel, the first of these influences probably plays a not unimportant part ; but in such metals as bismuth, antimony, and tellurium, the second must entirely predominate.

XXI. *Observations on the Height, Length, and Velocity of Ocean Waves. By* Hon. RALPH ABERCROMBY, *F. R. Met. Soc.**

THE interest in ocean waves has so much declined in recent years, that physicists have perhaps scarcely realized how much more easily measurements can be taken now than formerly.

In the old days wave-heights could only be ascertained, more or less, by estimation ; while the length and speed could only be determined by a common watch. Now-a-days the aneroid can easily measure small vertical heights to within one or two feet ; while the fly-back chronograph enables time to be measured to the $\frac{1}{5}$th second, without taking the eye for one moment off the object to be watched.

The following observations were taken on board the S.S. 'Tongariro,' in various parts of the S. Pacific between New Zealand and Cape Horn, in the month of June 1885.

Height was measured by a $4\frac{1}{2}$-inch aneroid with a very open scale, divided to the $\frac{1}{100}$th inch ; so that the readings could be taken at a glance to 0·025 inch, or, when time allowed, to 0·020. The instrument is an extremely good and accurate barometer. The altitudes were all calculated on the simple assumption that a difference of 1 foot in height is given by a difference of 0·001 inch of pressure. Any error which could arise between this reduction and that by a more rigorous method would be far less than the other errors of observation.

* Read February 25, 1888.